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Experimental Design in reservoir simulation: an integrated solution for uncertainty analysis, a case study

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Abstract Quantification of uncertain parameters in oil reservoirs is one of the major issues of concern. In underdeveloped reservoirs, there are many uncertain parameters affecting production forecast which plays a main role in reservoir management and decision making in development plan. To study the effect of uncertain parameters on the behavior of a reservoir and to forecast the probabilistic production of the reservoir, the simulator has to be run too many times with different entries for uncertain parameters. To avoid this heavy and time-consuming process, Experimental Design methodology is used which chooses the values of uncertain parameters from their ranges in a way that the total uncertainty in the system is captured with the least number of simulator runs. In this study, Experimental Design methodology is used to observe the effect of uncertain parameters on the production of an underdeveloped oil reservoir, which is subjected to immiscible gas injection method, and to estimate the probabilistic production of the reservoir; therefore, the proper and unbiased decisions for oil reservoir development can be made. Experimental Design methodology, as a powerful and trusted method, makes it possible to choose simulator runs so as to obtain accurate probabilistic production diagrams using the least number of runs as well as to study the impact of uncertain parameters on the oil reservoir production profile, quickly.

Keywords Uncertainty analysis · Experimental Design · Sensitivity analysis · Reservoir simulation · Immiscible gas injection

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List of symbols

COP	Cumulative oil production
GU	General uncertainty
MULTPV	Pore volume multiplier
MULTX	Transmissibility multiplier in X direction
MULTY	Transmissibility multiplier in Y direction
MULTZ	Transmissibility multiplier in Z direction
MULTFLT	Transmissibility multiplier for fault
BHPinj	Bottom hole pressure of injection well
Qinj	Surface injection rate
Pia	Aquifer productivity index
Va	Initial volume of water in aquifer
SGCR	Critical gas saturation
OIP	Oil in place
PV	Pore volume
S_o	Oil saturation
S_w	Water saturation
S_g	Gas saturation
B_o	Oil formation volume factor
DC	Production due to rock compaction
DW	Production due to water influx
DG	Production due to gas influx
DE	Production due to oil expansion
DS	Production due to solution gas

Introduction

In recent years, immiscible gas injection, as an effective method for enhanced oil recovery, has been used in many oil reservoirs. To optimize the development plan for an underdeveloped reservoir associated with many uncertain parameters and subjected to this method of enhanced oil recovery, it is necessary to determine the effect of uncertain parameters on the behavior of the oil reservoir.

Studying all of these uncertain parameters is an inefficient and time-consuming process. The main idea in this study is to find the major uncertain parameters with the most significant effect on the reservoir behavior.

To study the effect of these main uncertain parameters as well as to acquire the probabilistic production forecast, it is a good idea to use effective simulator runs to trap the whole uncertainty instead of running the simulator thousands of times with diverse entries for uncertain parameters.

Experimental Design methodology is able to select the effective uncertain parameters and to study their effect on the reservoir production with the minimum number of simulator runs.

Experimental Design methodology has already been applied in petroleum industry. For example, Experimental Design has been used to develop a polynomial model. This model has been then used to analyze the uncertainty available in the reservoir (Damsleth et al. 1991; Venkataraman 2000; Kabir et al. 2002) and also used for optimization (Dejean and Blanc 1999; White and Royer 2003; Zhang et al. 2007). In addition, Experimental Design has been combined with response surface to assess uncertainty in reservoir (Fetel and Caumon 2008). Moreover, Experimental Design has been used to eliminate options which impacted negatively on project economics and to select those that added net present value and to optimize development plan of reservoir (Kloosterman et al. 2007, 2008). In one research, a response surface was generated using Experimental Design. This response surface was used for improving development plan of agbami field (Spokes et al. 2004). In another research, Experimental Design was used to assess the uncertainty in a carbonate oil reservoir under water injection (Tabari 2010).

In this study, Experimental Design methodology is directly applied for uncertainty investigation in an underdeveloped oil reservoir which is subjected to immiscible gas injection method to take a step towards developing this reservoir.

Experimental Design methodology

Experimental Design method distributes the simulation runs within uncertain ranges of parameters efficiently, thereby minimizes the number of required runs for studying an uncertain system (Steppan et al. 1998). In fact, this methodology provides a quantified decision-based plan for minimizing risk in oil reservoirs (Kloosterman et al. 2008).

In this study, one variable at a time design is used for choosing the most effective uncertain parameters on the reservoir behavior. Furthermore, the inscribed central composite design and three-level full factorial design are combined to study the impact of effective uncertain parameters on reservoir production forecast.

Dena field specifications

This study has been performed on an underdeveloped oil reservoir, subjected to immiscible gas injection method, and situated in the southern part of Iran (Fig. 1). The specifications of this reservoir are presented in Table 1.

Sensitivity analysis

Many uncertain parameters are present in the simulation of Dena reservoir. The corresponding Ranges of these parameters, obtained from analogous reservoirs, are presented in Table 2.

In this stage, one variable at a time design is used to choose the uncertain parameters with the most significant effect on the specified outcome (herein, COP). The present study uses this design with a slight difference: instead of medium entries, base entries are used. Moreover, the case with all parameters at medium entries will be omitted from this design.

Various entries for uncertain parameters, which have been chosen according to this design, and forecasted COP values by the simulator, are presented in Table 3.

According to Figs. 2, 3 and 4, which are the results of the sensitivity analysis, it is clear that MULTPV, MULTZ, Qinj and SGCR parameters have the most significant effect on the COP in the 4th, 8th and 12th years from the beginning of simulation in Dena reservoir. The method for calculating the effect of uncertain parameters on the COP has been explained in Appendix. These effective parameters will be studied in the next stages.

Uncertainty analysis

Dena field is currently under development. The immiscible gas injection for pressure maintenance is considered for this field. A better understanding of the reservoir behavior with respect to the existing effective uncertain parameters and minimizing the effect of this uncertainty on production profile can help to improve Dena field development plan.

The objective in this stage is to study the impact of effective uncertain parameters, chosen in the previous stage, on the reservoir behavior and to acquire the probabilistic production diagrams for Dena reservoir. By integrating three-level full factorial and inscribed central composite designs, the entries for effective uncertain parameters from their ranges are chosen. The method of

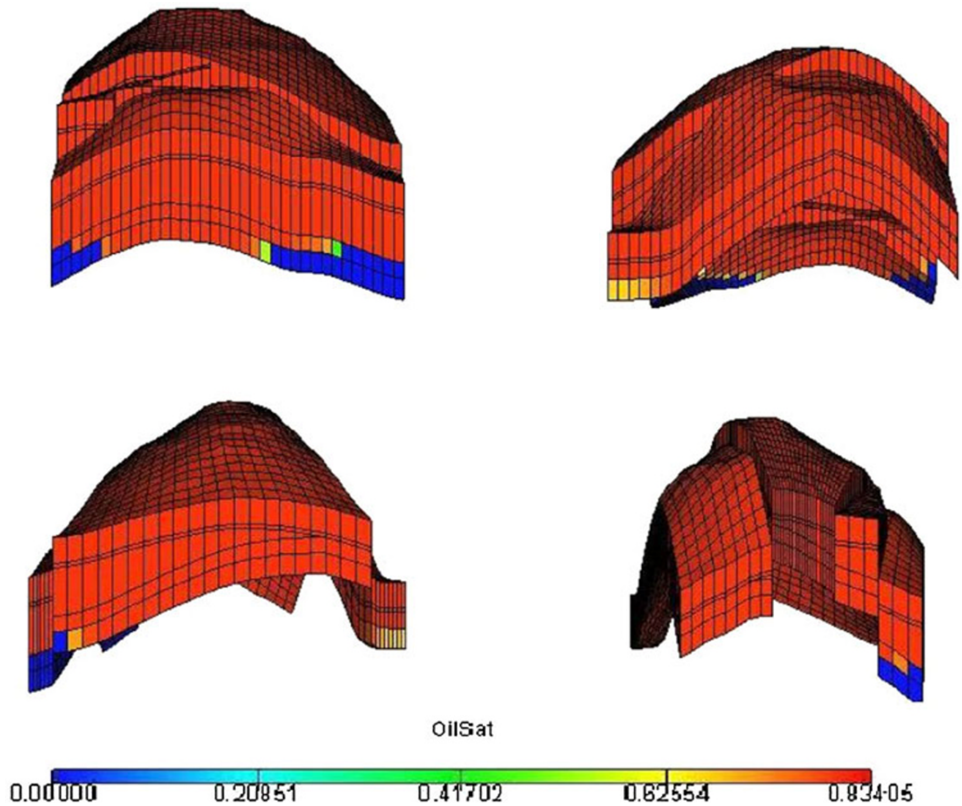

Fig. 1 Four views of Dena reservoir

Table 1 Characteristics of Dena field

Parameter	Value of the parameter
Location of the field	Southern part of Iran
Area of the field (km^2)	210
Gross thickness of the formation (m)	182
Average porosity of the formation (%)	27
Average permeability of the formation in X direction (mD)	14
Average permeability of the formation in Y direction (mD)	14
Average permeability of the formation in Z direction (mD)	71
Low water saturation (%)	20
Number of wells for oil production	12
Number of wells for gas injection	1

choosing uncertain parameters values based on integrating these two designs is presented in Tables 4 and 5. Subsequently, the simulator is run to calculate COP values corresponding to the chosen entries. In this study, Eclipse 100 has been employed as the simulator. Eclipse 100 calculates COP taking into consideration that the total oil produced equals the change in oil-in-place. These calculations have been explained in Eqs. 1 to 7 (Eclipse 2005).

Table 2 Minimum, base and maximum values for uncertain parameters existing in the simulation of Dena reservoir

Uncertain parameter	Minimum value	Base value	Maximum value
MULTPV	0.5	1	2
MULTX	0.5	1	2
MULTY	0.5	1	2
MULTZ	0.5	1	2
MULTFLT	0.5	1	2
BHPinj (Psia)	4,000	5,000	6,000
Qinj (Mscf/day)	1,000	5,000	10,000
Pia (STB/day/Psi)	10	200	400
Va (STB)	7E+07	7E+08	7E+09
SGCR	0.1	0.2	0.3

$$\mathrm{d(OIP)} = \mathrm{PV}^{t+\mathrm{d}t} S_\mathrm{o}^{t+\mathrm{d}t} [1/B_o]^{t+\mathrm{d}t} - \mathrm{PV}^t S_\mathrm{o}^t [1/B_\mathrm{o}]^t, \tag{1}$$

where

$$\begin{aligned} \mathrm{PV}^{t+\mathrm{d}t} &= \mathrm{PV}^t + \mathrm{d(PV)} \\ S_\mathrm{o}^{t+\mathrm{d}t} &= S_\mathrm{o}^t + \mathrm{d}(S_\mathrm{o}) \\ [1/B_o]^{t+\mathrm{d}t} &= [1/B_\mathrm{o}]^t + \mathrm{d}[1/B_\mathrm{o}] \end{aligned} \tag{2}$$

Substituting this equation into Eq. 1, we have

$$\begin{aligned} \mathrm{d(OIP)} = {} & [\mathrm{PV} + \mathrm{d(PV)}][S_\mathrm{o} + \mathrm{d}(S_\mathrm{o})][(1/B_\mathrm{o}) + \mathrm{d}(1/B_\mathrm{o})] \\ & - [\mathrm{PV} S_\mathrm{o}(1/B_\mathrm{o})] \end{aligned} \tag{3}$$

Table 3 Values of COP, calculated by simulator, corresponding to various values of uncertain parameters which are selected based on one variable at a time design

MULTPV	MULTX	MULTY	MULTZ	MULTFLT	BHPinj	Qinj	Pia	Va	SGCR	COP after 4 years (STB)	COP after 8 years (STB)	COP after 12 years (STB)
+1	0	0	0	0	0	0	0	0	0	15898508	33090864	47734612
−1	0	0	0	0	0	0	0	0	0	12799578	24386626	33867964
0	+1	0	0	0	0	0	0	0	0	14131435	29233024	41012624
0	−1	0	0	0	0	0	0	0	0	13992454	28839466	39969692
0	0	+1	0	0	0	0	0	0	0	14148386	28264708	41256968
0	0	−1	0	0	0	0	0	0	0	13993905	27823774	39882720
0	0	0	+1	0	0	0	0	0	0	15375486	31294306	44569036
0	0	0	−1	0	0	0	0	0	0	13510327	26250094	36799040
0	0	0	0	+1	0	0	0	0	0	14599191	29001026	40869236
0	0	0	0	−1	0	0	0	0	0	14455951	28695374	40432100
0	0	0	0	0	+1	0	0	0	0	14537121	28868602	40678432
0	0	0	0	0	−1	0	0	0	0	14437271	28699240	40473240
0	0	0	0	0	0	+1	0	0	0	14913045	30525334	43463004
0	0	0	0	0	0	−1	0	0	0	14267080	27781618	38541204
0	0	0	0	0	0	0	+1	0	0	14530310	28864704	40677280
0	0	0	0	0	0	0	−1	0	0	14491061	28678376	40354836
0	0	0	0	0	0	0	0	+1	0	14540457	28997110	41068692
0	0	0	0	0	0	0	0	−1	0	14493547	28624562	40172736
0	0	0	0	0	0	0	0	0	+1	14198728	28683066	40075848
0	0	0	0	0	0	0	0	0	−1	14761498	30615244	44939368

−1, +1, 0 represent minimum, maximum and base values, respectively

Expanding the Eq. 3,

$$\begin{aligned}\mathrm{d(OIP)} &= \mathrm{d(PV)}S_o^t[1/B_o]^t + \mathrm{d(PV)}S_o^t d[1/B_o] \\ &+ \mathrm{PV}^t \mathrm{d}(S_o)[1/B_o]^t + \mathrm{d(PV)}\mathrm{d}(S_o)[1/B_o]^t \\ &+ \mathrm{PV}^t S_o^t \mathrm{d}[1/B_o] + \mathrm{PV}^t \mathrm{d}(S_o)\mathrm{d}[1/B_o] \\ &+ \mathrm{d(PV)}\mathrm{d}(S_o)\mathrm{d}[1/B_o] \end{aligned} \tag{4}$$

The terms in this equation are associated with the various production mechanisms. These mechanisms are introduced in the following:

$$\begin{aligned}\mathrm{DC} &= -\mathrm{d(PV)}S_o^t[1/B_o]^{t+\mathrm{d}t} \\ \mathrm{DS} &= -\mathrm{PV}^{t+\mathrm{d}t}\mathrm{d}(S_o)[1/B_o]^t \\ \mathrm{DE} &= -\mathrm{PV}^t S_o^{t+\mathrm{d}t}\mathrm{d}[1/B_o] - \mathrm{d(PV)}\mathrm{d}(S_o)\mathrm{d}[1/B_o] \end{aligned} \tag{5}$$

Now, we know that

$$\mathrm{d}(S_o) = -\mathrm{d}(S_w) - \mathrm{d}(S_g) \tag{6}$$

Therefore,

$$\begin{aligned}\mathrm{DC} &= -\mathrm{d(PV)}S_o^t[1/B_o]^{t+\mathrm{d}t} \\ \mathrm{DW} &= \mathrm{PV}^{t+\mathrm{d}t}\mathrm{d}(S_w)[1/B_o]^t \\ \mathrm{DG} &= \mathrm{PV}^{t+\mathrm{d}t}\mathrm{d}(S_g)[1/B_o]^t \\ \mathrm{DE} &= -\mathrm{PV}^t S_o^{t+\mathrm{d}t}\mathrm{d}[1/B_o] - \mathrm{d(PV)}\mathrm{d}(S_o)\mathrm{d}[1/B_o] \end{aligned} \tag{7}$$

Now, using the simulator outcomes, the probabilistic production diagrams of Dena reservoir for the 4th, 8th and 12th years from the beginning of the simulation will be forecasted (Figs. 5, 6, 7).

According to Figs. 5, 6 and 7, the uncertainty for COP is very high and the forecasted COP values vary from 11439804 STB to 17282130 STB for the 4th year, 19941184 STB to 36872300 STB for the 8th year and 25958506 STB to 54636132 STB for the 12th year from the beginning of simulation. This is due to the uncertainty, present in the reservoir.

According to Figs. 5, 6 and 7, GU is calculated using the following relationship (Dejean J and Blanc 1999):

$$\mathrm{GU} = \frac{\mathrm{COP(max)} - \mathrm{COP(min)}}{(\mathrm{COP(max)} + \mathrm{COP(min)})/2} \tag{8}$$

Therefore, GUs at the 4th, 8th and 12th years from the beginning of the simulation are 41, 60 and 71 %, respectively, which are all high values.

The maximum value for COP at the 12th year is related to the maximum values for MULTPV, MULTZ, Qinj and the minimum value for SGCR from their ranges.

Since MULTPV, MULTZ and SGCR parameters are uncontrollable, the medium values of these parameters are

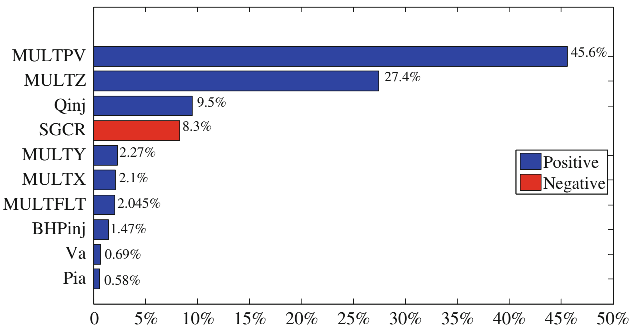

Fig. 2 Sensitivity study showing the effect of uncertain parameters on COP after 4 years from the beginning of simulation

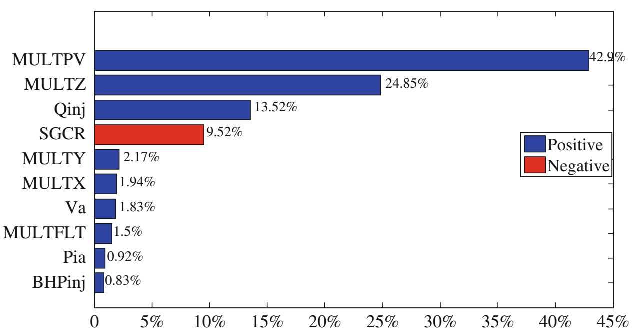

Fig. 3 Sensitivity study showing the effect of uncertain parameters on COP after 8 years from the beginning of simulation

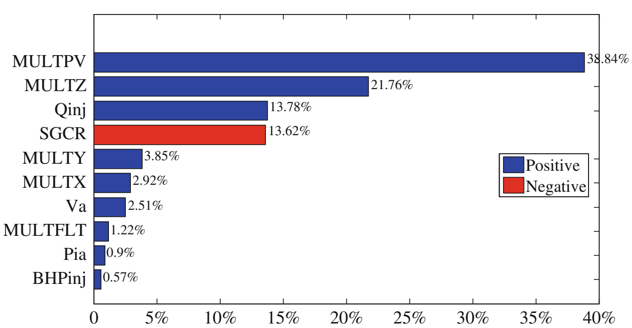

Fig. 4 Sensitivity study showing the effect of uncertain parameters on COP after 12 years from the beginning of simulation

used and the effect of different Qinj values on the COP will be examined.

According to Fig. 8, as expected, increase in the value of Qinj is associated with increase in oil production, so that the maximum value of COP will be acquired at Qinj = 10,000 Mscf/day.

In another research (Moeinikia and Alizadeh 2011), a proxy model has been developed by artificial neural network in Dena reservoir. This artificial neural network was run 20,000 times to acquire the entire range of probabilistic production forecast. According to those diagrams, it was concluded that COP values vary from 1.1534e+007STB to 1.7484e+007STB for the 4th year, 2.1080e+007STB to 3.7598e+007STB for the 8th year and 2.6901e+007STB to 6.0888e+007STB for the 12th year. These results are very close to the ones in this study. It confirms that the probabilistic production diagrams in this study, which have been obtained by simulation runs chosen according to Experimental Design methodology, are valid and accurate and cover the whole range of probabilistic production forecast.

Developing an artificial neural network as a proxy model to acquire these diagrams has difficulties such as training of artificial neural network. In addition, developing other proxy models may cause the results to be far from the simulation ones and this leads to wrong results. On the other hand, running a simulator thousands of times, to acquire these diagrams, is very time consuming and expensive. The results of this study show that by direct employment of Experimental Design methodology, one can get the accurate results with the least number of simulation runs instead of running the simulator numerous times or developing a proxy model.

The Integration of three-level full factorial and inscribed central composite designs, which has been employed in this study, provides three inner points within uncertain ranges of parameters and also includes all combinations of parameters values; therefore, one can be more sure that the whole range and also the interaction of uncertain parameters have been covered compared to the other designs in which just one center point and border points are provided to study.

Results and discussion

Dena reservoir, which is under immiscible gas injection method, is an underdeveloped reservoir with many uncertain parameters.

The key idea in this study was to use one variable at a time design to choose the most effective uncertain parameters on reservoir behavior. Using this design, MULTPV, MULTZ, Qinj and SGCR parameters are identified as the most effective parameters relating to COP in this reservoir.

To make efficient decisions over the reservoir development plan, the most effective uncertain parameters on the reservoir behavior must be studied and the probabilistic production of the reservoir has to be forecasted. Experimental Design methodology, as a fast and reliable method for obtaining probabilistic results, seems a proper idea for dealing with uncertainty.

In this study, integrating three-level full factorial and inscribed central composite designs, as well as utilizing a simulator, were used to forecast the probabilistic

Table 4 Values of uncertain parameters selected based on three-level full factorial design

RUN	MULTPV	MULTZ	SGCR	Qinj	RUN	MULTPV	MULTZ	SGCR	Qijn
1	−1	−1	−1	−1	42	−1	0	−1	0
2	−1	−1	−1	1	43	1	0	−1	0
3	−1	−1	1	−1	44	−1	0	1	0
4	−1	−1	1	1	45	0	1	0	1
5	−1	1	−1	−1	46	0	−1	0	−1
6	−1	1	−1	1	47	0	1	0	−1
7	−1	1	1	−1	48	0	−1	0	1
8	−1	1	1	1	49	−1	−1	−1	0
9	1	−1	−1	−1	50	−1	−1	1	0
10	1	−1	−1	1	51	−1	1	−1	0
11	1	−1	1	−1	52	−1	1	1	0
12	1	−1	1	1	53	1	−1	−1	0
13	1	1	−1	−1	54	1	−1	1	0
14	1	1	−1	1	55	1	1	−1	0
15	1	1	1	−1	56	1	1	1	0
16	1	1	1	1	57	0	−1	−1	−1
17	1	0	0	0	58	0	−1	−1	1
18	−1	0	0	0	59	0	−1	1	−1
19	0	1	0	0	60	0	−1	1	1
20	0	−1	0	0	61	0	1	−1	−1
21	0	0	1	0	62	0	1	−1	1
22	0	0	−1	0	63	0	1	1	−1
23	0	0	0	1	64	0	1	1	1
24	0	0	0	−1	65	−1	0	−1	−1
25	1	1	0	0	66	−1	0	−1	1
26	−1	−1	0	0	67	−1	0	1	−1
27	1	−1	0	0	68	−1	0	1	1
28	−1	1	0	0	69	1	0	−1	−1
29	0	0	1	1	70	1	0	−1	1
30	0	0	−1	−1	71	1	0	1	−1
31	0	0	1	−1	72	1	0	1	1
32	0	0	−1	1	73	−1	−1	0	−1
33	1	0	0	1	74	−1	−1	0	1
34	−1	0	0	−1	75	−1	1	0	−1
35	1	0	0	−1	76	−1	1	0	1
36	−1	0	0	1	77	1	−1	0	−1
37	0	1	1	0	78	1	−1	0	1
38	0	−1	−1	0	79	1	1	0	−1
39	0	1	−1	0	80	1	1	0	1
40	0	−1	1	0	81	0	0	0	0
41	1	0	1	0					

−1, +1, 0 represent minimum, maximum and medium values, respectively

production of Dena reservoir and also to study the effect of the existing uncertainty in the reservoir on the probabilistic production forecast.

As predicted, the uncertainty on the reservoir COP was very high. Moreover, as time goes by, the uncertainty of COP will increase.

Table 5 Values of uncertain parameters selected based on inscribed central composite design

RUN	MULTPV	MULTZ	SGCR	Qinj	RUN	MULTPV	MULTZ	SGCR	Qijn
1	−1	−1	−1	−1	15	1	1	1	−1
2	−1	−1	−1	1	16	1	1	1	1
3	−1	−1	1	−1	17	2	0	0	0
4	−1	−1	1	1	18	−2	0	0	0
5	−1	1	−1	−1	19	0	2	0	0
6	−1	1	−1	1	20	0	−2	0	0
7	−1	1	1	−1	21	0	0	2	0
8	−1	1	1	1	22	0	0	−2	0
9	1	−1	−1	−1	23	0	0	0	2
10	1	−1	−1	1	24	0	0	0	−2
11	1	−1	1	−1	25	0	0	0	0
12	1	−1	1	1	26	0	0	0	0
13	1	1	−1	−1	27	0	0	0	0
14	1	1	−1	1	28	0	0	0	0

±2, ±1 and 0 represent extreme, inner and medium points, respectively

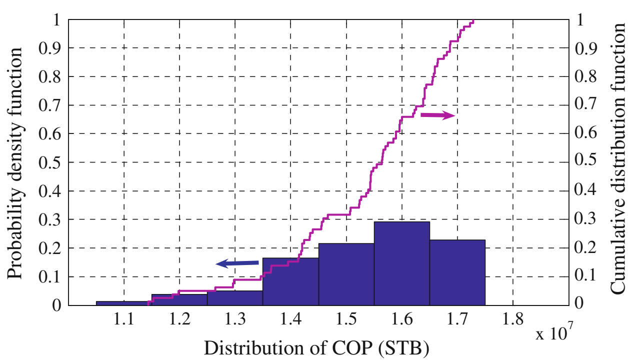

Fig. 5 Probability distribution for COP after 4 years from the beginning of simulation

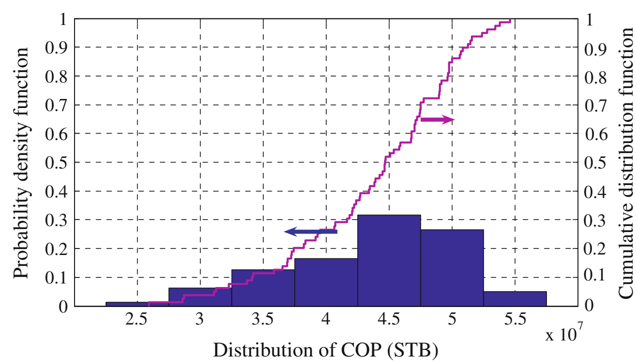

Fig. 7 Probability distribution for COP after 12 years from the beginning of simulation

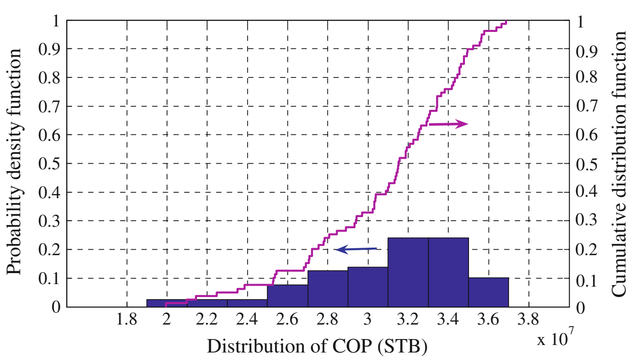

Fig. 6 Probability distribution for COP after 8 years from the beginning of simulation

The results of probabilistic production diagrams in this study were compared to the diagrams, which have been obtained by artificial neural network, and it was observed that these results are nearly the same; therefore, it confirms that direct use of Experimental Design is a trusted and easy method for obtaining the probabilistic production forecast.

Conclusions

Experimental Design methodology covers the whole uncertainty available in the system with the minimum number of simulator runs. Actually, this method, as an unbiased approach, has the potential of adding useful information to the reservoir development plan and also, of saving considerable time. As a result, it is an efficient method for studying underdeveloped reservoirs.

The main advantage of integrating three-level full factorial and inscribed central composite designs is that many

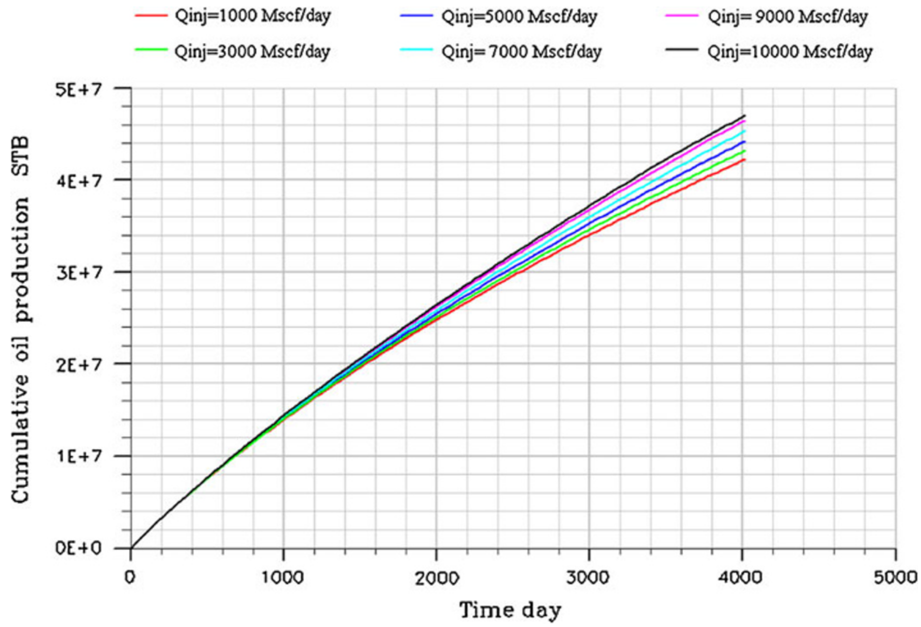

Fig. 8 Sensitivity of COP after 12 years from the beginning of simulation with respect to the different values of Qinj

inner and border points are presented to study; therefore, it traps the non-linear effect in the system, and presents useful information for optimizing the development plan of Dena reservoir.

Using one variable at a time design, it can be observed that Pia, Va, BHPinj and MULTFLT parameters have the least effect on Dena reservoir development plan. On the other hand, MULTPV, MULTZ, Qinj and SGCR parameters have major effect on the development and future production of this reservoir.

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Appendix: effect of uncertain parameters on COP

Substituting the COP values presented in Table 3, which have been obtained by simulator, into the following equations, we can calculate the effect of uncertain parameters on COP.

$$\text{Effect of uncertain parameter on COP} = \frac{\text{main effect of uncertain parameter on COP}}{\sum|\text{main effect of uncertain parameter on COP}|}, \quad (9)$$

where

$$\text{Main effect of uncertain parameter on COP} = \text{COP}_{(\text{maximum value of uncertain parameter})} - \text{COP}_{(\text{minimum value of uncertain parameter})} \quad (10)$$

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